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PATUXENT RIVER, MARYLAND

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AN ASSESSMENT OF SEMICONDUCTOR DIODE LASER PAINT REMOVAL APPLIED TO FIBERGLASS/EPOXY SUBSTRATES

by

Steven J. Hartle
Joseph Kozol, Navmar Applied Sciences Corporation
Frederick A. Lancaster, Lancorp Advanced Systems, Inc.

4 September 2003

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14. ABSTRACT

High power semiconductor diode laser technology has matured to the point of feasibility for application to organic coatings removal from aircraft metallic and composite materials. This program evaluated the operating characteristics and the effects of diode laser paint removal on flexural strength and microstructure of fiberglass/epoxy composite.

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Contents

INTRODUCTION

Laser decoating is a nonintrusive, nonkinetic energy process that generates a highly collimated, monochromatic beam of light that can be used to remove coatings from a variety of substrates such as composites, fiberglass, metals, and plastics. By focusing the beam into a footprint of high energy density, the high level absorption of energy at the surface of a coating results in the subsequent decomposition and removal of the coating. Since the applied energy is mostly absorbed and used in coating decomposition, the substrate is expected to experience only a minimal increase in temperature. The ablation process includes instant pyrolization and evaporation, which carries away most of the radiation energy and results in combustion by-products such as carbon monoxide, nitrous oxides, and carbon dioxide (CO_2). The only solid waste associated with this process is the ablated coating that is vacuumed and captured in particle filters while the effluent can be processed through standard particulate filtration.

Lasers are currently being used in various manufacturing operations, including welding, drilling, and surface treatment. The use of laser energy to strip coatings has been under development primarily for the needs of the aerospace industry but is now being used to replace conventional depainting methods for other applications as well. A laser decoating system suitable for aircraft paint removal includes a laser, a beam delivery system, a manipulation system, and an effluent capture system. Stripping lasers, unlike lasers used for machining, are characterized by a high depth of field beam, with a flat, uniform energy distribution and little fringing around the edges. The operation is line of sight.

Laser technology for organic coatings removal from aircraft has now progressed to levels of commercial availability and suitability for engineering evaluation for specific applications. This program provided a preliminary assessment of the capabilities of direct diode laser stripping.

OBJECTIVE

The objective of this program was to assess the status and screen the operating characteristics of diode laser paint removal and the effects on flexural strength and microstructure of representative composite radome substrates.

DIODE LASER TECHNOLOGY

The semiconductor diode laser (referred to as diode laser) is contained on a small wafer of semiconductor material, such as gallium arsenide, less than a millimeter thick. When excited by the application of an electrical charge, a coherent, homogeneous beam of light is produced. These wafers can be stacked into linear arrays to provide power into the kilowatt range. Due to the small size of the laser diodes, they can be packaged into very small housings, which simplifies handling and beam control. Some of the applications of low power diode lasers in the milliwatt range are barcode scanners, laser pointers, fiber optic transmissions, and reading compact discs. The past several years have brought about the introduction of reduced cost, high power laser diodes in the watt and kilowatt range for uses in welding, cutting, drilling, and surface treatment.

When compared to other industrial lasers in use today, diode lasers offer several advantages. Diode lasers can be constructed to have the same wavelengths as the commonly used Nd:YAG laser at any wavelength from 800 to 1,064 nm. Unlike other lasers that operate at one wavelength, diodes of various wavelengths can be stacked and used together. Diode lasers can perform all of the tasks that Nd:YAG lasers can perform as well as the CO_2 laser, with the advantage of energy efficiency. Over 50% of the input energy is converted to output energy for the diode laser as opposed to the Nd:YAG and CO_2 lasers which achieve about 12% efficiency. Therefore, high power diode lasers are able to operate at lower voltages (110 V single phase or 208 V three phase) as opposed to other lasers of comparable power, which must operate at higher voltages and require large chilling units to provide cooling to the laser components. Consequently, this allows for the power supplies of diode lasers to be more compact and for ramp-up time to be instantaneous without a conditioning period. The characteristics indicate that diode lasers are capable of being integrated into a portable unit applicable to on-aircraft operation with powers in excess of 1 kW.

Diode lasers, as opposed to other lasers, do not require complicated optic packages to form the beam to the shape of a uniform line for paint stripping or cleaning. In relation to paint stripping or surface treatment, the beam from the diode laser needs only to be collimated and focused onto the surface through one lens on the diode wafer and one at the workhead. This results in a wide line of near homogeneous energy with little fringing on the edges. The diode laser uses simple lens packages to focus the beam, adding to the simplicity of function and maintenance.

Diode lasers are relatively safe and easy to maintain. Shock hazards in maintenance are minimized because the laser is solid state and energy efficient and has small power supplies. The diode bars have a minimum working life of 10,000 hr or 5 years of daily use and replacement takes about 3 hr. Annual maintenance consists of replacing the water filter in the chiller and checking the laser power. Daily maintenance requires cleaning the optics window and checking the system components.

TEST PANEL PREPARATION

Testing was performed on fiberglass/epoxy panels coated with epoxy primer and polyurethane topcoat. The composite material used for this evaluation was S2/8552 fiberglass epoxy resin, with a surface sensitive layup: $[0_2,+45-45 \text{ deg}, 0 \text{ deg},+45-45 \text{ deg}]_s$. Panels were cut to 12 in. x 12 in. and coated as follows:

Epoxy primer, Waterborne, MIL-PRF-85582C, Ty I
Polyurethane Topcoat, MIL-PRF-85285C, Ty I
Total thickness of 0.010-0.015 in. (0.254-0.381 mm)

After coating, panels were air dried at room temperature for 1 week and baked at 150°F (66°C) for 1 week.

SYSTEM DESCRIPTION

Panels were stripped in a robotic workcell using a Nuvonyx, Inc. 4-kW semiconductor diode laser, operated in the pulsed mode of operation. The laser beam spot was focused to 13 mm x 1 mm, with a 1 mm overlap between passes. Previous tests on various Navy aircraft coatings indicated that this spot size is optimum and allows for variation in surface profile. The diode laser was fixed to the end of a 6-axis robot, which manipulated the laser beam across the test panel at a set distance of approximately 3.5 in. (89 mm) from the surface. The panels were placed on a work platen and clamped to the surface. A blowoff nozzle was placed on the end of the laser to ensure that the effluent was evacuated from the surface and into the vacuum system. This was affixed to the laser workhead to blow across the panel. The test arrangement is shown in figure 1.

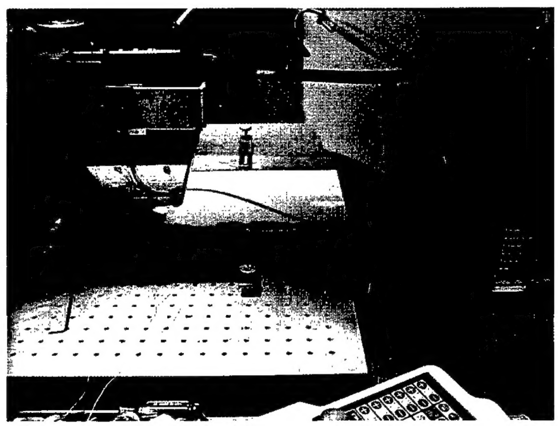

Figure 1. Test Arrangement

PAINT STRIPPING PROCEDURE

The traverse speed of the robot was manipulated from 10 m/min up to 20 m/min. The laser was pulsed at 6000 Hz and 150 μsec, resulting in a 90% duty cycle (on-time). The power was varied between 1 – 2 kW. As the panels were stripped, surface temperature measurements were made with a Raytec hand-held infrared pyrometer. The readings were taken by manually following the laser beam and reading directly behind it at a range of 6-12 in. (152-305 mm) from the surface. Temperatures measured indicated peak surface temperature, which dropped off rapidly as the beam passed by. In addition, one setup panel was instrumented with thermocouples inserted from the reverse side. Holes were drilled in four locations on the reverse side of the panel and one thermocouple was inserted approximately 2 mils (0.05 mm) under the surface and a second was inserted approximately 5-6 mils (0.127-0.152 mm) under the surface in each location.

LASER STRIPPING TEST RESULTS

INSTRUMENTED SETUP PANEL 100105

Panel 100105, used as a setup panel, was instrumented with four sets of thermocouples as described in the previous paragraph. The first of four sections was stripped to the substrate with six passes at 1 kW and 10 m/min traverse speed. During setup, the time between passes was approximately 1 min. The maximum surface temperature recorded with the IR pyrometer was 146°F (63.3°C). The maximum thermocouple reading, recorded during the sixth and final pass, was 138°F (58.9°C). Temperature measurements on the first section of the setup panel are shown in figure 2.

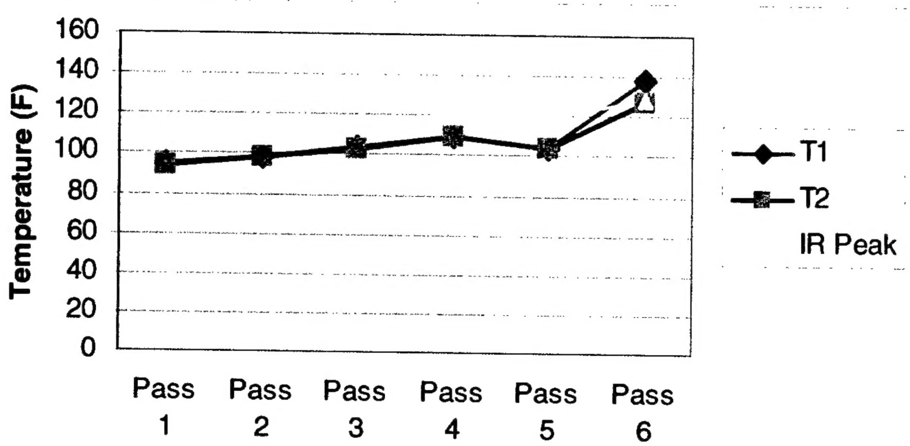

Figure 2. Setup Panel 100105 Temperature Measurements

The subsurface temperature readings are designated T1 and T2. The temperatures recorded did not indicate a potential problem in overheating the composite substrate during stripping. The power and pulse parameters used for the remaining sections of the instrumented setup panel were found to be invalid, due to an undetected software error. This was subsequently corrected for stripping of two test panels, numbered 100110 and 100107, which were stripped with optimized parameters. The test panels had been coated with 10-15 mils (0.254-0.381 mm) of primer and topcoat, representative of repeated painting in service. These panels were retained after stripping, along with unpainted controls, for fabrication of specimens for flexure testing in order to reveal any effects of surface substrate degradation. Coating layering and thickness effects on paint removal rates and substrate properties were not evaluated in these screening tests.

TEST PANEL 100110 - 1 kW PAINT REMOVAL

Panel 100110 was stripped at a power level of 1 kW, with a pulse rate of 6000 Hz for 150 µsec and a traverse rate of 10 m/min. A total of six passes was used to strip each area to the substrate. The panel was stripped in two sections due to the programming arrangement; after

stripping one section, the panel was rotated 180 deg to strip the second section. Stripping was similar to the setup panel, with six passes required to remove the topcoat and primer to the substrate, as shown in figure 3. Strip rate for this panel was consistent for both sections of the panel. At a traverse rate of 10 m/min, each row was traversed in 1.5 sec for a total of 21.1 sec for the 14 rows in the first section. Six passes required a total strip time of 126.6 sec over an area of 0.417 ft^2. This equates to 0.197 ft^2/min (1.10 m^2/hr) to strip an average paint thickness of 13 mils (0.33 mm).

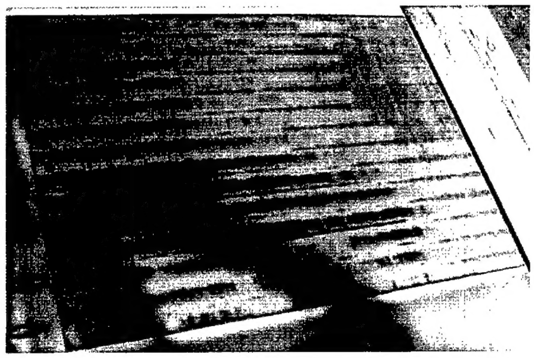

Figure 3. 1 kW Removal

Similarly, the second section of panel 100110 was 0.363 ft^2 in area and required 112.3 sec for six passes, equating to a strip rate of 0.194 ft^2/min (1.08 m^2/hr). Inasmuch as the strip rate follows a linear relationship with thickness, the approximate strip rate of 0.2 ft^2/min for an average thickness of 13 mils of paint equates to approximately 0.8 ft^2/min (4.46 m^2/hr) for a typical initial paint thickness of 3 mils (0.076 mm). By comparison, this rate is very close to that of plastic media blasting with acrylic media but without the added time for masking.

Temperature measurements during stripping of panel 100110 were made with a hand-held IR pyrometer and are shown in table 1. The maximum temperature recorded was below 160°F (71.1°C) and dropped over 30°F (17°C) within about 1 sec as the beam passed by at 10 m/min. The effects of extended dwell times on reduced traverse rates were not evaluated and could lead to greater heat input to the substrates with the potential for heat damage.

Table 1: Panel 100110 IR Pyrometer Readings, °F

	Pass1	Pass2	Pass3	Pass4	Pass5	Pass6
1st Section	131	151	145	140	154	158
2nd Section	138	141	142	143	144	151

TEST PANEL 100107 - 2 kW PAINT REMOVAL

Panel 100107 was stripped at a power level of 2 kWs, with a pulse rate of 6000 Hz for 150 μsec. This panel was also stripped in two sections and was rotated 180 deg to strip the second section. A total of three passes was made to strip the first section to the substrate, traversing at 10 m/min. Stripping of the first section in three passes demonstrated the linear relationship of laser power to removal rate, in comparison with 6 passes at 1 kW used to strip panel 100110. At a traverse rate of 10 m/min, each row was traversed in 1.4 sec, for a total strip time of 19.6 sec for the 14 rows in the first section. Three passes of the laser required 58.8 sec over an area of 0.385 ft^2 (0.036 m^2). This equates to 0.392 ft^2/min (2.18 m^2/hr) to strip an average paint thickness of 13 mils, approximately double the strip rate at 1 kW power level. The second section of panel 100107 was stripped in four passes; the first two at 10 m/min and the second two at 20 m/min. The passes were made over an area of 0.385 ft^2 (0.036 m^2) and took 19.6 sec per pass at 10 m/min and 9.8 sec per pass at 20 m/min. This equated to a total strip time of 58.8 sec, resulting in the same strip rate as the first section. The test panel is shown in figure 4.

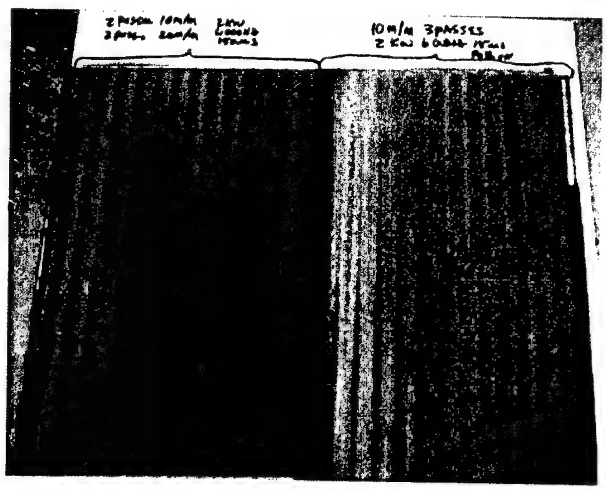

Figure 4. Panel 100107 2 kW Removal

Temperature measurements made with the hand-held IR pyrometer during stripping of Panel 100107 are shown in table 2. Results for the three passes in the first section showed that spike temperatures were somewhat higher than for the panel stripped at 1 kW but still not a cause for concern. For the second section, the final two passes at an increased traverse rate of 20 m/min limited the temperature rise closer to that of the panel stripped at 1 kW. In all cases, the peak temperature dropped significantly within 1 sec after the beam passed by. It was apparent that heat input to the substrate can be controlled by adjusting the traverse rate of the beam for a given power level.

Table 2: Panel 100107 Pyrometer Readings, °F

	Pass1	Pass2	Pass3	Pass4
1st Section	186	183	194	--
2nd Section	182	180	168	168

MECHANICAL TESTING

After stripping, flexural test specimens were cut from the panels on a conventional milling machine with a diamond grit blade to ensure parallel edges and to prevent edge delamination in cutting. Four point flexural tests were performed according to ASTM D790. A nonstandard 25:1 span to depth ratio was used to achieve correct compression failure mode on the stripped surface. Median flexure strengths are summarized in table 3, along with standard deviation and 95% confidence limits.

Table 3: Flexural Test Results

	Control	Panel 100110 1 kW	Panel 100107A 2 kW/10 m/m	Panel 100107B 2 kW/20 m/m
Median Flexural Strength, MPa	1154	1132	1180	1143
Standard Deviation, MPa	20.4	24.3	45.1	47.8
95% Confidence Limit, MPa	12.7	15.0	33.4	33.1

Results are illustrated in figure 5. The box shows the 95% confidence limits and the median value is shown within. At the 95% confidence level, laser stripping did not degrade the flexural strength of the fiberglass epoxy substrate, although stripping at 2 kW resulted in a significant increase in standard deviation.

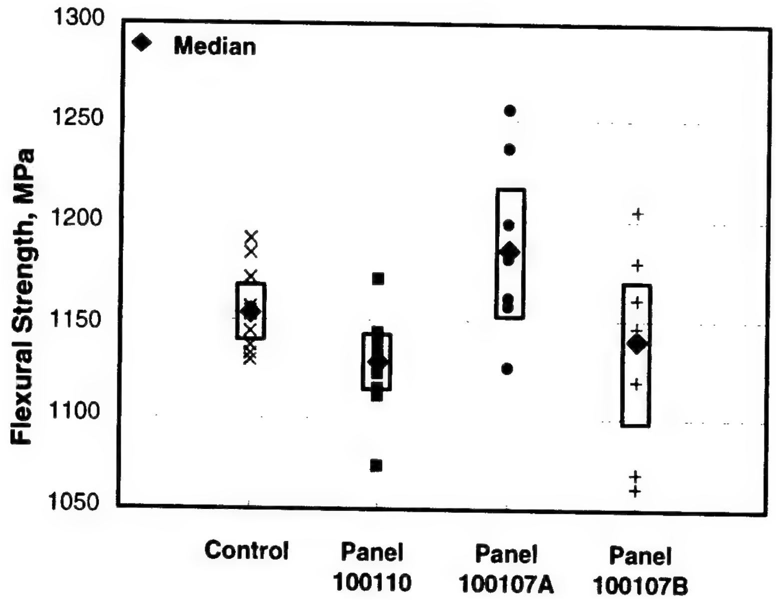

Figure 5. Flexural Test Results

MICROSTRUCTURAL EVALUATION

Surfaces of the composite panels were examined after laser stripping of primer and topcoat using optical microscopy. The control panel surface shows the pattern of the release ply in the gel coat layer prior to painting and stripping in figure 6. Figures 7, 8, and 9 show the surfaces of painted panels 100110, 100107A, and 100107B, respectively, after stripping completely to the substrate. This represents a worst case stripping condition. It may be seen that, under these conditions, the gel coat has been removed and the surface layer of fibers is visible. There is little or no apparent damage to the surface fibers as a result of the laser stripping. The efforts of repeated painting and stripping were not evaluated.

Figure 6. Control Panel

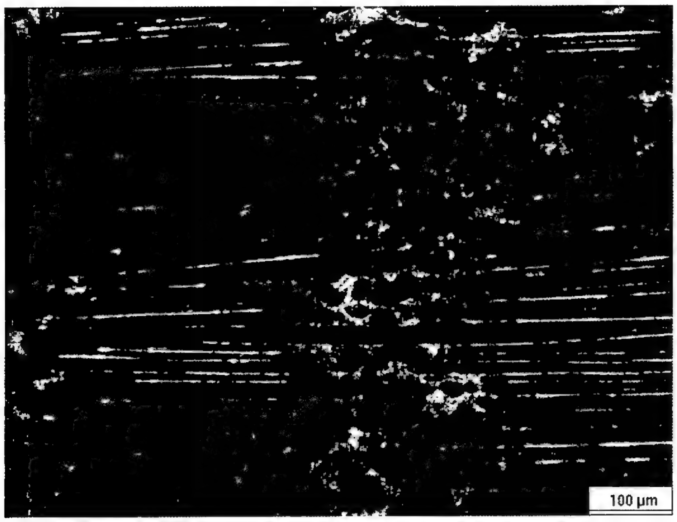

Figure 7. Panel 100110

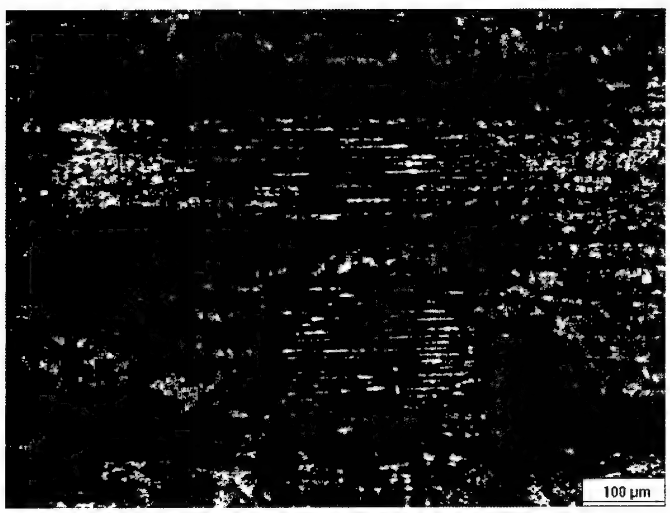

Figure 8. Panel 100107A

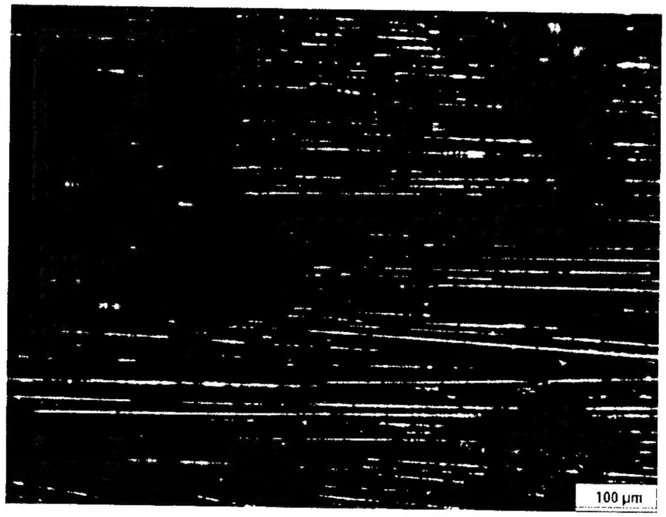

Figure 9. Panel 100107B

CONCLUSIONS

During the screening tests, paint removal rate doubled as the power of the laser doubled.

As the laser power increases, heat input to the surface increases for a constant traverse rate.

To increase the paint removal rate without increasing heat input, the power level and traverse rate can be increased proportionately.

These screening tests have indicated the potential of 1 kW or greater semiconductor diode laser stripping for effective and efficient precision aircraft coatings removal.

A comprehensive test program is needed to determine the effects of repeated painting and stripping on the mechanical properties of aircraft structural materials.

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